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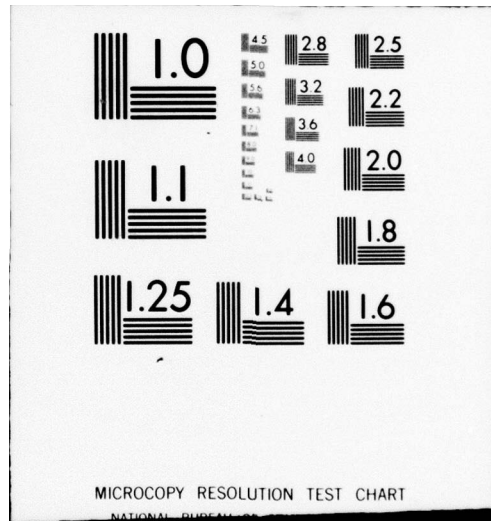UNCLASSIFIED

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This report provides a summary of the results of a study which explored the interaction of (Rayleigh) surface acoustic waves with the magnetic excitations of a ferromagnetic material.

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# Final Technical Report

Army Research Office Grant No. DAAG29-77-G-0101

D. L. Mills, Principal Investigator
Department of Physics
University of California
Irvine, California

## I.   Introduction

In the original proposal, we set forth a program of theoretical research centered on the analysis of the interaction of surface acoustic waves (Rayleigh waves) with spin waves in ferromagnetic materials. Through this interaction, by tuning an external magnetic field, in principle one may selectively attenuate the Rayleigh wave. Also, if the wave propagates on a ferromagnetic material with magnetization parallel to the surface, then for propagation perpendicular to the magnetization, the attenuation exhibits a left/right asymmetry. That is, the attenuation constant for a wave that propagates from left to right across the magnetization differs in value from that of a wave that propagates from right to left. Finally, there is the possibility that on magnetic substrates one may launch Rayleigh waves by driving the spins with a magnetic field. Thus, one may generate surface acoustic waves on non-piezoelectric materials by this means.

During the grant period, we have successfully completed the program set forth in the original proposal. The research on the coupling of surface acoustic waves to spin waves in thin films is described in two papers[1,2], and in a thesis submitted by R. E. Camley to the University of California at Irvine. Reprints of these papers have been supplied with earlier progress reports, and a copy of Dr. Camley's thesis has been attached to the present report.

We also completed a body of research on the theory of light scattering from spin waves on magnetic surfaces. Very recently, a beautiful series of experiments have studied spin waves on the surface of ferromagnets by this means.[3,4] The method explores precisely those features of the magnetic response central to the

principal concern of the program.  As a consequence, we have developed

a theoretical description of this phenomena.[5]  We are able to give

an excellent account of the existing data, and our work provides

a number of predictions on what future experiments may reveal.  We

have been pleased to learn recently that the main predictions of

our theory have been confirmed by new data.[6]  Also, the light

scattering method has been used recently to explore spin waves in

thin magnetic films of technological interest.[7]  The technique allows

the study of the magnetic response of films in a  manner not possible

with the older magnetic resonance method.

It is the view of the principal investigator that our work on

light scattering may emerge as the most significant body of research

to be completed during the grant period.  The experiments that pro-

voked this work appeared only after the program was underway, and

were unanticipated.  This illustrates how limited our view of the

future of a given area can be.  It is often impossible to predict signi-

ficant new developments in advance, though certain straightforward

extrapolations can be made.  The present program provides an example,

since it was funded to provide research directed toward a very

specific and pre-conceived application.  While the proposed research

was indeed completed, the most exciting information generated by

the work may be the  side-thrust that developed.  As one sees from

reference (7), this area is important not only from the point of

view of basic physics, but may make a practical and real impact

on magnetic materials research.  Had we initially proposed a pro-

gram built around light scattering from magnetic solids, it is

not clear to the principal investigator that the research would have been funded by ARO.

The experimental phase of the topic of light scattering from spin waves is also of interest, from the point of view of funding policies current in the U.S. To perform the measurements, a highly sophisticated Brillouin spectrometer is required. There are at least three such spectrometers currently operating in European laboratories, but none in the U.S. Thus, we are unable to participate in the new era of Brillouin scattering that is emerging in Europe. It is the understanding of the principal investigator that people at the IBM Yorktown Heights laboratory are eager to pursue the study of light scattering from spin waves in films. It will be necessary to take the spectra in Germany, although the basic design parameters of the spectrometer were described in the literature many years ago.[8] This is one consequence of the very limited capital equipment money available to U.S. laboratories in recent years. Even our leading experimentalists find it difficult to generate the funds necessary to keep their laboratories current and competitive with those elsewhere.

## III. Research Results

The purpose of the program was to explore the interaction of (Rayleigh) surface acoustic waves with the magnetic excitations of a ferromagnetic material.

Our first theoretical study[1] considered the propagation of surface acoustic waves on a semi-infinite ferromagnet, with magnetization parallel to the surface, and parallel to a principal axis of the presumed cubic substrate. For parameters characteristic of YIG, we explored the magnitude of the attenuation and phase velocity changes produced by magnetoelastic excitation of the spin system by the strain field associated with the Rayleigh wave. The frequency variation of the attenuation, its variation with magnetic field and propagation angle were analyzed in detail.

The left-right asymmetry discussed in the introduction is a particularly striking feature of the results. For example, if the surface acoustic wave (SAW) propagates from left to right across the magnetization, there is a sharp attenuation peak at the frequency $\gamma(H_o + 2\pi M_s)$, where $H_o$ is the strength of an externally applied magnetic field, $M_s$ is the magnetization of the substrate, and $\gamma$ is the gyromagnetic ratio. This attenuation peak has its origin in the coupling between the SAW and a surface spin wave (the Damon-Eshbach wave). This attenuation peak is completely absent when the SAW propagates from right to left across the magnetization. There is also a broad attenuation peak from coupling between the SAW, and bulk spin waves. The first theoretical study[1] funded by the present proposal explored the influence of exchange coupling on these features in the attenuation and dispersion introduced by magnetoelastic coupling between the SAW and spins.

Of considerably greater practical interest is our detailed analysis[2] of the attenuation and dispersion of a SAW propagating on a nonmagnetic substrate upon which a thin magnetic film has been placed. This configuration is more likely to be the one encountered in a practical device. While the earlier studies of propagation on a semi-infinite substrate provide one a useful qualitative guide for what to expect for the two layer geometry, a rich variety of new phenomena enter when one examines the film in detail. For example, the broad featureless attenuation peak produced by coupling of the SAW to the bulk spin waves in the semi-infinite structure now acquires complex structure, since the spin wave spectrum of the thin film consists of a series of discrete standing spin wave resonances, rather than the continuum present for the semi-infinite case. In addition, there are now two surface spin waves, one localized predominantly on the upper surface and one on the lower surface. Thus, one has two modes, each of which is sensitive to the environment at one of the two interfaces.

The frequency or magnetic field variation of the attenuation now becomes quite complicated, with a series of attenuation peaks produced by coupling of the acoustical strains to the various surface waves and standing wave resonances of the film structure. The left/right asymmetry is always present, for the film as well as the semi-infinite geometry. Since the position of each peak may be controlled by variation of an external magnetic field, we believe that one has the possibility of introducing attenuation (or dispersion) selectively into SAW devices in a wide variety of ways. Note that we are considering here high frequency surface acoustic waves, which have frequencies comparable to the ferromagnetic resurance structures

in the response of the film. Our theoretical studies outline the
expectations for a geometry of practical importance, thin films of
YIG overlaid on a YAG or GGG substrate.

In the calculations above, it is necessary to construct theoretical
models of the magnetic response of the ferromagnetic film. A number
of features of the problem are well understood, as are the values
of the principal parameters that enter the analysis. However, one
feature critical to the analysis is poorly understood, and may
actually vary from sample to sample. This is the strength of the
"spin pinning fields" which operate at the surface of the film,
or at the film/substrate interface. In our analysis of the propagation
characteristics of the SAW, we can generate a wide variety of re-
sults, depending on how we model the pinning fields.

The light scattering method referred to in Section I provides a
means of directly studying the magnetic response of the film/substrate
combination, and can directly explore the question of the strength
of the spin pinning at surfaces and interfaces.

The experiment is the study of the inelastic scattering of
light by spin waves on the surface of a ferromagnet, or in a film.
One directs laser photons at the film, and studies the frequency
spectrum of backscattered light. The shape of this spectrum, when
fully analyzed, provides quantitative information on the magnetic
parameters of the film or magnetic substrate, included the degree
of spin pinning present.

We have developed a quantitative theory of light scattering
from spin waves,[5] and applied the theory to an analysis of data
on EuS surfaces, and on Fe. We are able to provide a quantitative

account of the data available to date[3,4], and recent experiments carried out in response to our theory have verified some critical predictions[6], though quantitative contact between the theory and the new data awaits further calculation.

In a ferromagnet, the mechanism responsible for scattering light is modulation of the dielectric tensor by thermal fluctuations in the spin system. If we let $\delta\epsilon_{\mu\nu}(\vec{x},t)$ be the time and space variation of the dielectric tensor produced by motion of the spins, and if $S_\lambda(\vec{x},t)$ is the $\lambda^{th}$ Cartesian component of spin density, then we can have an expansion of the form

$$\delta\epsilon_{\mu\nu}(\vec{x},t) = \sum_\lambda K_{\mu\nu\lambda}S_\lambda(\vec{x}\,t) + \sum_{\lambda\delta} G_{\mu\nu\lambda\delta}S_\lambda(\vec{x}\,t)\,S_\delta(\vec{x}\,t)$$

where $K_{\mu\nu\lambda}$ and $G_{\mu\nu\lambda\delta}$ are tensors that may be measured by various optical optical methods.

If the fluctuating dielectric tensor is inserted into Maxwell's equation, the angular distribution and frequency variation of the scattered radiation may be derived through use of methods developed by our group some years ago.[9] We have carried out rather extensive numerical studies of the shape of the spectrum, and the influence of various material parameters on it, for both EuO and Fe.

In this section of the final report, we have outlined the research completed with ARO support. A detailed description of the results is contained in the Progress Reports, the preprints and reprints submitted to ARO, and in the thesis submitted by Dr. R. E. Camley to the University of California at Irvine. A copy of this thesis is attached to this report.

### III. <u>Personnel Supported by the Grant</u>

The only person who received salary support from the grant is R. E. Camley, who was a graduate student at the time the research was performed. The copies of research forms the thesis submitted by Dr. Camley to the University of California at Irvine.

During the early months of the project, we enjoyed the assistance and advice of Dr. R. Q. Scott, who had completed earlier theoretical work on surface magnetoelastic waves. The principal investigator was an active collaborator on the theory of light scattering from spin waves.

We are pleased to see that Dr. Camley has been invited to present a paper at the upcoming Joint Intermag/MMM Conference to be held in New York this coming spring.

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